
Chapter 6

Comminution Engineering

Comminution Engineering

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Summary

Comminution engineering describes the processes for the size reduction of bulk materials. The materials are crushed in one or several steps to the feed size required for the grinding process. In the grinding systems of a cement manufacturing plant the materials are ground to either raw meal or cement.

Crushing is characterized by the application of either compression or impact forces whereas grinding is effected with a combination of impact and friction forces.

Comminution theories have been developed in an attempt to determine the energy input required to crush or to grind a material of a given feed size to the required product fineness. These theories are only valid for a rather limited range of materials and of size-reduction-machine types and are therefore not suitable for the dimensioning of industrial machines.

Based on comminution theories and empirical findings several laboratory tests have been developed to measure the energy input required for a given size reduction.

The ground or crushed product can be characterized by its particle size distribution (PSD) and/or by the new surface produced in the comminution process.

1. INTRODUCTION

Comminution engineering, also known as size-reduction engineering, is defined as the designing and analyzing of processes for the breakdown of bulk solids into smaller / finer particles, without changing their state of aggregation.

Comminution is a major unit operation in a cement manufacturing plant, accounting for about 50 % - 75 % of plant electrical energy consumption.

The comminution processes are divided, depending on feed-material size, into the crushing (breaking) processes and the grinding (pulverizing) processes.

In the following pages especially the processes, theories and laboratory tests relevant for grinding are dealt with. The crushing aspects will only briefly be mentioned.

2. COMMINATION PROCESSES

The comminution processes in a cement production line are divided into four main groups depending on kind of material to be processed and feed material size. The four main comminution processes are:

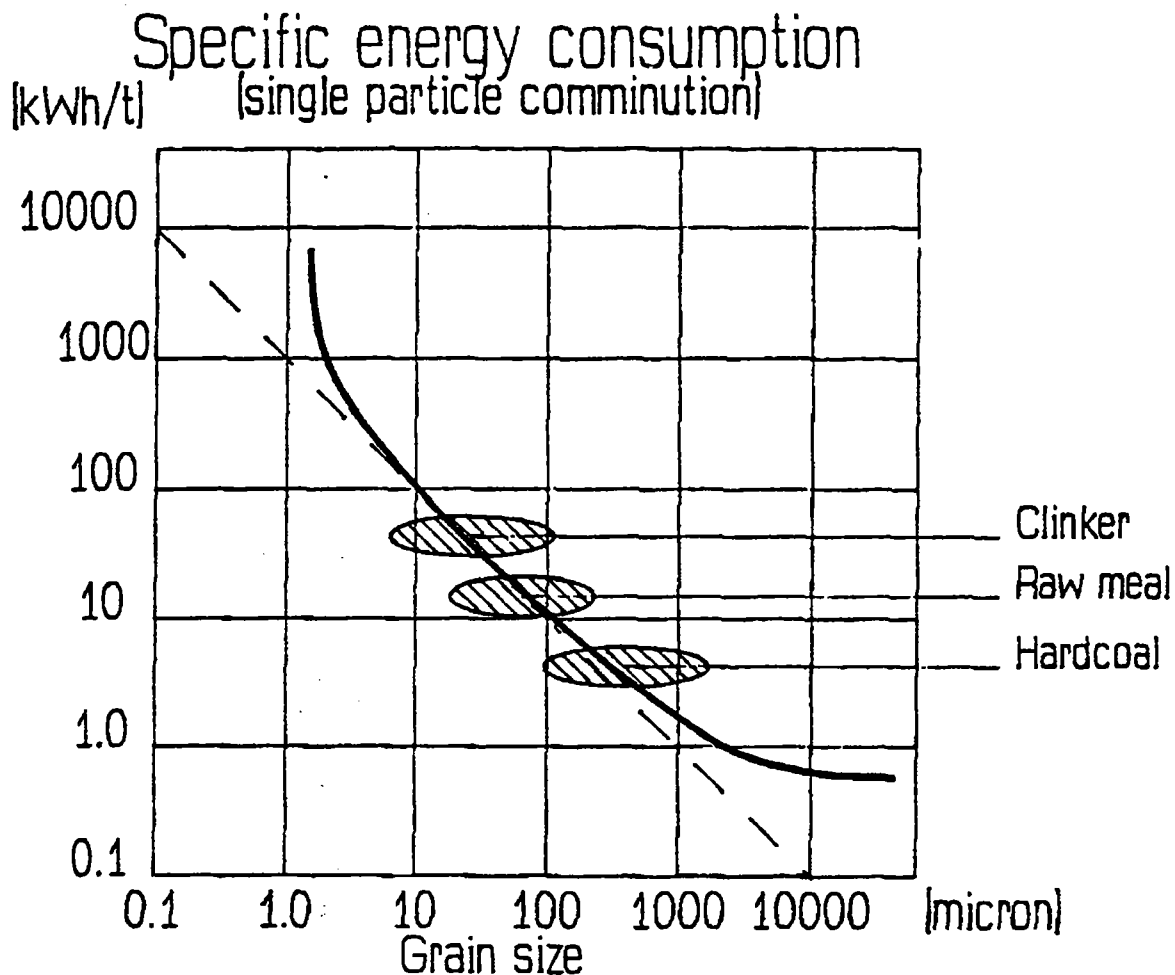
- 1) Crushing of rock materials from the quarry (size 1 - 1.5 m) in one till three steps to an intermediate raw material state (size < 100 mm), used as input for the raw meal production process.
- 2) Grinding of the intermediate raw material to raw meal (< 2 % 12 200 μ m), which degree of fineness is defined by the following kiln-firing process used.
- 3) Grinding (and simultaneously mixing) of clinker and additives (size < 25 mm) to the final product, cement, which degree of fineness is defined either by standards or customer requirements.
- 4) Grinding of raw coal (size 20 mm) to coal powder used for kiln firing.

It is obvious that the great difference between these four comminution processes will affect the electrical energy consumption, machinery design, machinery wear and process heat consumption.

The following approximate rates of specific power consumption per ton cement production shows the distribution of energy between individual comminution processes and gives an indication on where energy can be saved.

Raw material crushing:	1 - 2 kWh/t clinker
Raw material grinding:	5 - 15 kWh/t clinker
Coal grinding:	2 - 4 kWh/t clinker
Cement grinding:	30 - 60 kWh/t clinker
Cement plant total:	90 - 130 kWh/t clinker

A lot of attempts have been made to obtain a thorough knowledge about the energy required for comminution of a known material bed consisting of determined product particle size distribution (PSD), but till now nobody has been successful in stating a valid theory.



3. COMMUNUTION METHODS

The most known comminution forces are:

- 1) Compression forces
- 2) Friction / Shear forces
- 3) Inter-particle contact forces
- 4) Impact forces

A crushing process is often characterized by the application of a single type of comminution force, whereas a grinding process is mostly characterized by the application of a combination of above comminution forces, e.g. compression - friction - shear (roller mill) or impact-friction (ball mill).

An important fact is that impact comminution processes tend to produce a greater amount of fine particles than a compression comminution process.

Note that at time there are no evidences, that the feed particle shape affects a grinding process. This is not the case for crushing processes.

Some comminution forces and machines are shown in fig. 1.

The selection of the adequate grinding machinery / method principally depends on three types of parameters; material, process and environmental parameters.

Material parameters:

- * Chemical composition (SiO_2)
- * Mineralogical composition (Moisture)
- * Physical properties (Strength, Abrasiveness)
- * Possible time-dependent variations of above parameters

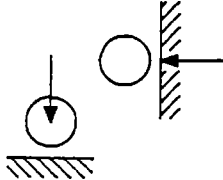
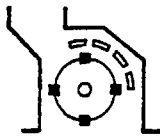
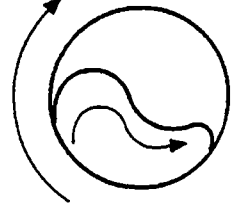
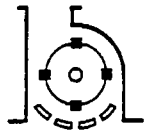
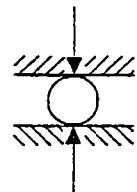
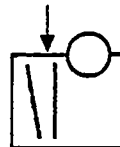
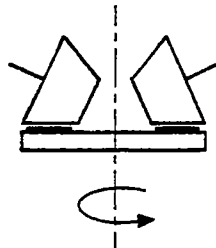

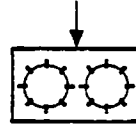
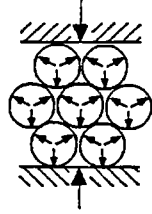
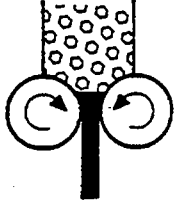
Process parameters:

- * Comminution-, drying-, feeding- and wear behavior of input material
- * Requirements on fineness, homogeneity of output material for further processing.

Environmental parameters:

- * Life cycle costs (investment, operation, maintenance)
- * Specific energy consumption (kWh/ton throughput)
- * Noise level, space requirements

Figure 1

COMMINUTION FORCE	COMMINUTION MACHINE		PROD.	
	CRUSHING (> 30 mm)	GRINDING (< 30 mm)		
IMPACT 	IMPACT CRUSHER 	TUBE MILL 	CEMENT	
	HAMMER CRUSHER 			
COMPRESSION 	JAW CRUSHER 	ROLLER MILL 		RAW MEAL/CEMENT
	CONE CRUSHER 			
	ROLLER CRUSHER 			
INTERPARTICLE FORCES 		ROLLER PRESS 		RAW MEAL

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4. COMMUNUTION THEORIES

Comminution theories are trying to explain / describe the relationship between process energy input and change of material PSD. Only a small portion of the energy input in a comminution process is converted into actual comminution work. Main reasons for the poor energy utilization are:

- Mechanical losses (gears, transmission, etc.) 5 % - 10 %
- Material handling, drying and de-dusting 80 % - 95 %
- Noise emission
- Poor distribution of comminution forces to every single particle in particle bed

4.1 Energy

As mentioned earlier the energy requirements for a comminution process varies over a wide range.

To give an idea about how and why the energy consumption varies so much, some ‘laws of comminution’ are presented. These are all based on the relationship between the changes in particle size and energy consumption.

In 1967 RITTINGER presented the so called ‘First law of comminution’, which postulates that the new surface created by the comminution process is directly proportional to the energy input. This means that the energy input, E_R , is inversely proportional to the decrease in particle size.

$$W_R \sim \frac{1}{X_2} - \frac{1}{X_1}$$

In 1885 KICK presented the ‘Second law of comminution’, which in contrast to Rittingers ‘law’, postulates that the energy input is proportional to the particle volume reduction during the comminution process.

$$W_k \sim \ln \left(\frac{X_1}{X_2} \right)$$

In 1961 BOND presented the ‘Third law of comminution’ postulating that the energy input is proportional to the new crack length created by the comminution process. This gives that for particles of a similar shape the energy input is inversely proportional to the square root of the average change in PSD.

$$W_B = E_B \left[\frac{10}{\sqrt{X_{80,P}}} - \frac{10}{\sqrt{X_{80,P}}} \right]$$

E_B = BOND's workability index

X_{80} = 80 % passing [μm]

W_B = specific comminution energy [kWh/t]

The Bond workability index, E_B (or W_i) is derived from the Bond grindability test, which simulates, on a laboratory scale, closed circuit grinding. When using the Bond index, E_B , in above specific energy formula, it should be kept in mind that a certain index value, E_B , can only be used with the same material and with a size reduction range close to the one used when the grindability test was carried out.

Note that the above described ‘laws’ are no laws, but approximations and/or empirical findings.

4.2 Energy Utilization

The energy utilization, E_u , is the quotient of the new created specific surface and the specific energy used hereof.

$$E_u = \frac{\Delta S}{W_s \cdot 3,6} [cm/J]$$

$$\Delta S = SSB_{Prod} - SSB_{Feed} [cm^2/g]$$

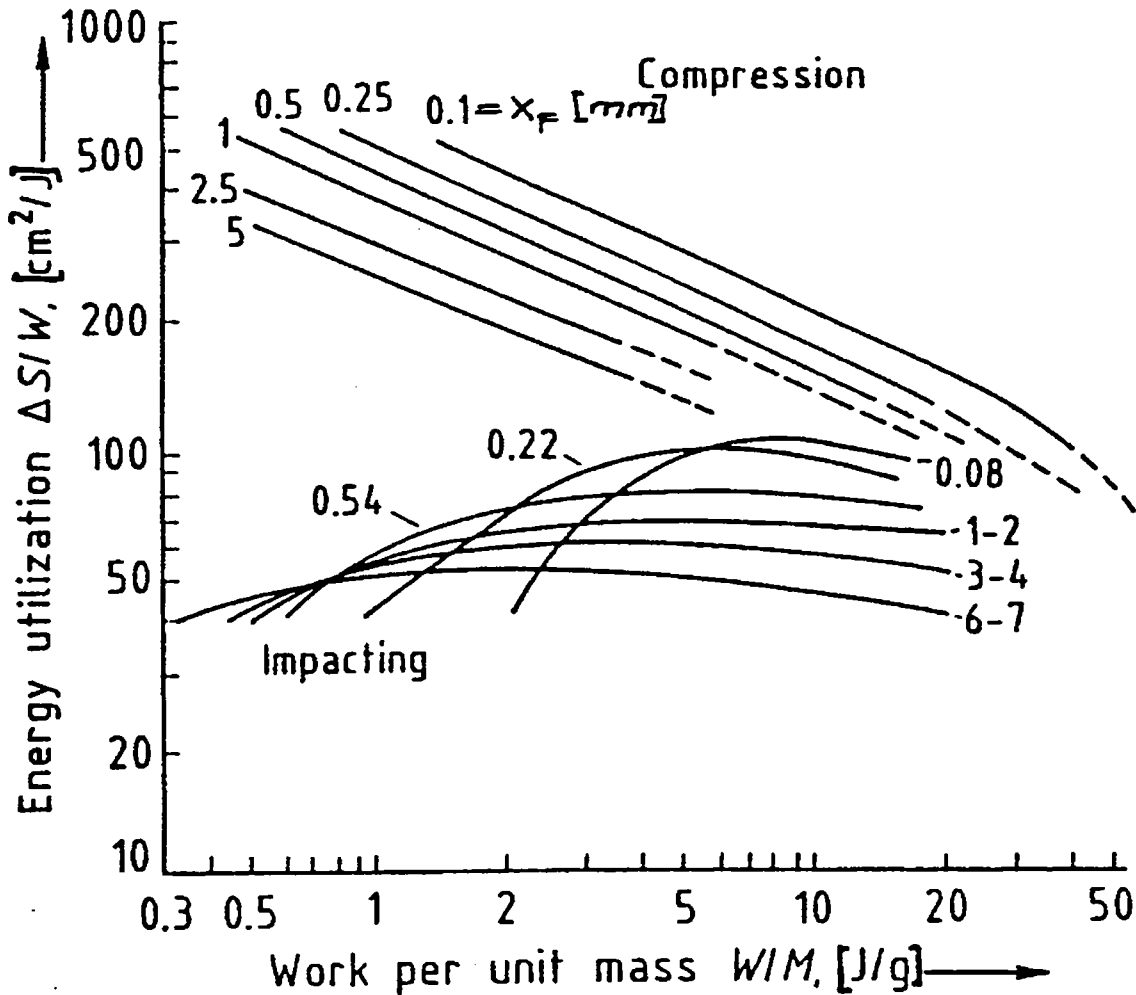
$$W_s = \text{specific energy [kWh/t]}$$

The energy utilisation value can only be used to compare comminution process, where material with the same chemical/mineralogical composition and feed size is used.

Note the specific surface value used in above formulas is the SSB (according to Blaine). Since there are a lot of different methods to obtain the specific surface value, the method used in each case must be specified. If the specific surface value is obtained through calculation, SSC, using the powder's PSD, the following conversion formula can be used:

$$SSB = \frac{SSC - 807}{12}; SSC = 807 + 1,2SSB$$

Figure 2 Energy Utilization, Limestone (Single Particle Comminution)



4.3 Efficiency

The comminution efficiency, η_c , is defined as the relation between ‘the theoretical energy input’ and ‘the actually process input energy’.

$$\eta_c = E_i / E_p$$

where

E_i = theoretical energy input

E_p = actual energy input

The theoretical energy input is defined as ‘the least energy input required to over-come a single particles strength and break it into smaller pieces’ and the actual process energy input is defined as ‘the mill shaft energy input’.

The comminution efficiency depends, apart from material properties, strongly on the material PSD, on type of comminution machine and on operational state. Note, that the theoretically calculated input energy is more representative for coarse crushing than for fine grinding, as shown below.

Based on investigations on single particle comminution, STARHAND indicated the following ranges of comminution efficiency for some industrial comminution machinery.

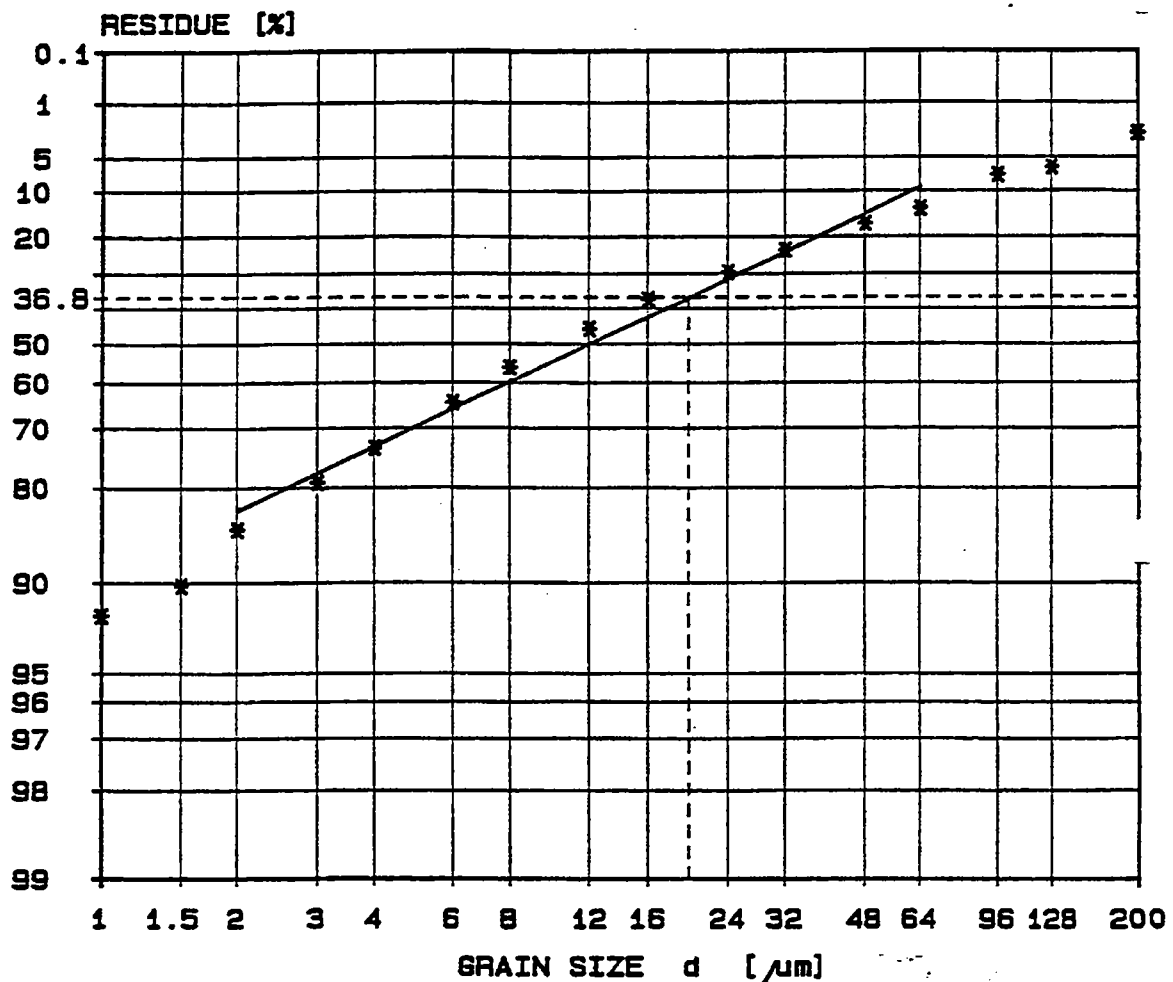
Jaw and Roller crusher	70 - 90 %
Impact crusher	30 - 40 %
Hammer crusher	15 - 25 %
Roller press	10 - 20 % F
Vertical roller mill	7 - 15 %
Tube mill	6 - 9 %

5. PARTICLE SIZE DISTRIBUTION

The Particle Size Distribution (PSD) is one of the most important parameters affecting a comminution process. This is why it is important to depict a PSD and characterize it by means of some significant values in the cement industry.

In the cement manufacturing industry the following ways of describing a PSD are commonly used.

For coarse materials the PSD is usually plotted in a LIN/LIN or LIN/LOG - diagram, as shown above. Significant values for such a PSD are the cumulative percentage of residue on a standard sieves or the sieve size at a given percentage of residue (R 10 %, R 5 %, R 25 mm, etc.).



GRAIN SIZE DISTRIBUTION ACCORDING ROSIN-RAMMLER-SPERLING

SCREENING METHOD: LASER GRANULOMETRE 715 CILAS

SLOPE n : 0.74 [-]
GRAIN SIZE d' : 19.6 [μm]

For very fine materials, like cement products, the PSD is plotted in a so called RRSB-grid 1), because herein a fine PSD tend to correlate with a straight line. This type of diagram has a double logarithmic ordinate (y-axis) and a logarithmic abscissa (x-axis). After linear regression of the PSD, the slope, n , of the straight line can be calculated. This slope, together with the particle size, d' , at 63.2 % cumulative passing (36.8 % residue) are significant values for a PSD, stating its location (μm) and degree of distribution (wide-narrow).

The RRSB - formula

$$\ln \left[\ln \left(\frac{100}{R_d} \right) \right] = n [\ln(d) - \ln(d')]$$

- R_d = % of particles with diameter greater than d (residue)
particle size in microns μm
- d = particle size in microns, such that 36, 8% of the particles have a size greater than d'
- d' = slope of RR straight line
- n =

6. COMMINUTION PROCESS OPTIMIZATION

Before trying to optimize a comminution process, or any other process, it is essential to record the actual working state, to determine the working state of comminution machine, some process values are compared against values from other processes. Since there is no detailed knowledge about energy consumption for comminution, values like energy consumption, energy efficiency and energy utilization have to be compared with and related to other values, obtained under similar conditions.

Generally optimizing means that an industrial comminution process, which is fed with a preset and fixed material PSD, is manipulated in such a way, that it uses a less total energy input to, simultaneously, produce a greater amount of particles finer than set size.

The common ways of optimizing a comminution process are:

- * Closed loop grinding, with separator
- * Narrower PSD, giving less fines / less energy consumption
- * Change of comminution machinery (upgrading)
- * No 'overgrinding'
- * Avoiding stochastic grinding force application

7. LABORATORY TESTS

7.1 General

The comminution theories, dealt with earlier, are empirically found and based on the knowledge of basic material parameters such as PSD, specific surface, grindability, abrasiveness, moisture content, etc.

Therefore the laboratory tests described below constitutes, together with practical comminution experience, a vital 'base of knowledge' for the design and improvement of comminution machines and processes.

All the tests described herein are performed at the HMC's laboratories.

7.2 Particle Size Analysis

Since the materials used in cement manufacturing are mostly compounds, with any kind of Particle Size Distribution, it is essential to be able to determine the actual feed PSD and the transformations in the PSD during the comminution process.

The PSD is determined by sieving the material on several sieves, with different mesh sizes, and recording the weight passing or retaining on each sieve. It is obvious that the smaller the sieve size mesh intervals the better the PSD is depicted.

Below table summarizes the most common sieving methods.

Sieving method	Sieve range [micron]	Sample [gram]	Test time [min]
Mechanical (dry sieving)	33 - 2000	50	60
Alpine, air-jet (dry)	33 - 2000	50	60
Supersonic (wet sieving)	2 - 40	2,0	180
Sedigraf (wet)	0,1 - 300	1,0	60
Laser, Cilas (wet)	1 - 200	1,0	20
Laser, Sympatec (dry or wet)	1 - 875	(wet) 1,0 (dry) 50	20 8

After determining the PSD, by any of above listed test methods, it is essential to plot the PSD in a diagram and to calculate some significant PSD-values. Usually the cumulative percentage passing or residing on a sieve is plotted against the particle diameter (mesh size). Depending on the material fineness a suitable diagram is chosen.

7.3 Specific Surface

The Specific Surface according to Blaine (SSB) is at time the most common single parameter for characterization of a cement and its behavior. The SSB-value indicates the magnitude of a powder's total particle surface per weight unit (cm²/g).

Note, that if two powders, with the same chemical composition, are characterized by the same SSB-value, this does not necessarily mean that they have the same PSD.

The SSB-value is obtained by measuring the powder's air permeability with the test equipment shown in appendix. The measuring itself is performed by recording the time, t, needed for a specified amount of air to pass through the test sample in the permeability cell. The recorded time is indirectly proportional to the powder's specific surface.

The specific surface of a powder can also be calculated from a known PSD. Since, the individual particles in a powder mostly have an irregular form the formula for calculation of the SSC-value is extended with a form factor, f.

The SSC-value is also strongly influenced by the material density. At HMC the SSC-values are calculated with below formula, under the assumptions that the particles are all spherical (f = 1) and that the powder has a standard density (= 3.1 g/cm³).

$$SSC = \frac{6f}{\rho} \cdot \sum_{i=1}^{16} \frac{R_i - R_{i+1}}{\frac{1}{2}(d_i + d_{i+1})}$$

f: form factor (=1)

ρ: specific density off cement (g/cm³)

R_i % of particles with diameter (microns) greater than d_i (i = 1,2,3...,16)

d_i particle equivalent diameter (d_i = 0.1, 0.3, 1, 1, 5, 2, 3, 4,....., 196)

For cements about 60 % of the calculated specific surface originate from particles less than 3 μm, which shows how essential it is to standardize the calculation formula to be able to compare SSC-values.

The correlation between the SSB-value and the SSC-value is shown by below empirical formula, which has been derived from great sample of cements with different PSD.

$$SSC = 807 + 1.2 \times SSB$$

$$SSB = (SSC - 807) / 1.2$$

Note that a SSB-value is not the same as Specific Surface Calculated (SSC) value. The SSC-value is calculated from the PSD under the presumption that the particles have a spherical form, and usually indicates a greater total specific surface.

7.4 Grindability Test

The grindability is defined as 'the resistance behavior against size reduction of a material (or particle) in a grinding process'. Quantitatively the grindability is expressed as 'energy input' (energy consumption) required for the size reduction of one mass unit of material. The energy input depends of course on the type of mill and on the type of material to be ground.

Several grindability tests have been developed to simulate, on a laboratory scale, the industrial grinding performance. The material to be investigated is tested under strict observation of the relevant test conditions. The values means of scale-up factors.

7.4.1 “Holderbank” Grindability Test

The basic test method was introduced by MITTAG and further developed at “Holderbank”, Technical center.

Test equipment

Test mill: Ø 0.5 x 0.5 m
Mill speed: 37.8 min.⁻¹
Ball charge: 100 kg
Sample weight: 10 kg (< 12 mm)

Test procedure

In a first step, the material is ground with balls of Ø 70 mm (40 %) and Ø 40 mm (60 %) to a fineness of about 60 % residue on the 90 µm sieve. Then the balls are removed and cubes of 17 x 17 mm are used for the subsequent steps. After 200 - 300 revolutions the mill is stopped for sampling and a PSD-analysis as well as specific surface (Blaine)-analysis is performed.

Test evaluation

During the grinding periods the torque Md is measured at the mill shaft. The specific power consumption E_{spec.} can be calculated according to the following formula:

$$E_{spec} = \frac{Md \times \Delta n}{59,6} [kWh/t]$$

Md = torque on mill shaft [Nm]

n = number of revolutions of the mill in one grinding step

The specific energy consumption of the test mill has to be converted with a scale-up factor to obtain the specific energy consumption at the mill shaft of an industrial mill.

7.4.2 HARDGROVE - Grindability Test

The HARDGROVE test is based on the comminution law developed by RITTINGER.

Test equipment

- * Grinding bowl with 8 balls (\varnothing 25.4 mm)
- * Grinding ring driven by motor of 0.2 kW
- * Load of grinding ring on grinding bowl approx. 29 kg
- * Sample: 50 g (590 <x> 1190 μ m)

Test procedure

50 g of the material with a particle size limitation of minimum 590 μ m and maximum 1190 μ m is prepared and fed to the grinding bowl. After 60 revolutions the ground sample has to be removed from the bowl and the weight of material passing the 74 μ m sieve to be determined.

Test evaluation

The HARDGROVE index H can be calculated from the weight D of the tested sample passing the 74 μ m sieve.

$$H = 13 + 6.93 \times D$$

The HARDGROVE index H can be converted into the work index E_H :

$$E_H = 435 / (H^0 \times 82) \quad [\text{kWh/t}]$$

The specific power consumption E_{spec} can then be calculated:

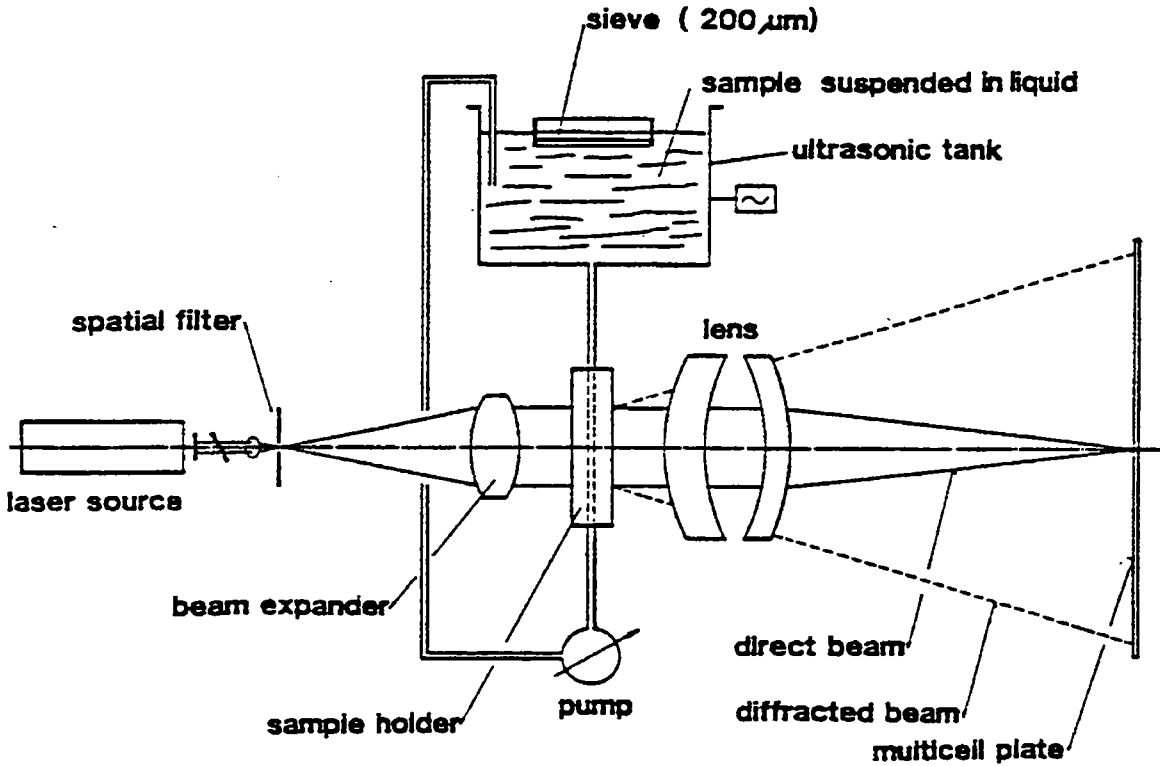
$$E_{spec} = E_H \left(\frac{10}{\sqrt{X_2}} - \frac{10}{\sqrt{X_1}} \right) [\text{kWh/t}]$$

PARTICLE SIZE DISTRIBUTION TEST

Test method: CILAS (Laser)

Purpose of the test: Determination of particle size distribution of cement and coal dust

Test equipment:



-
- Test procedure:
- Zero calibration of liquid
 - Sample preparation: 0.1 - 1.0 g (< 200 μm)
 - Test run
 - Automatic display of particle size distribution

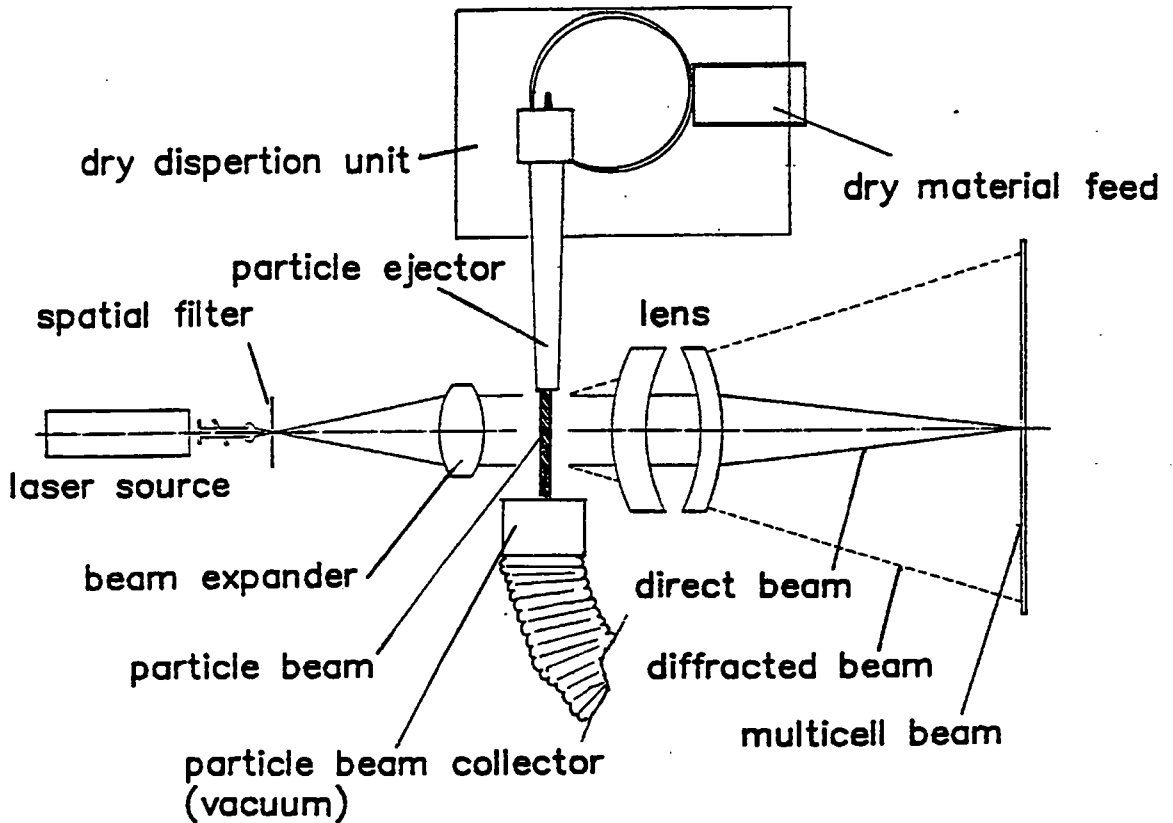
Total testing time (16 particle fractions): 10 min.
Sieve range: 1 - 180 μm

PARTICLE SIZE DISTRIBUTION TEST

Test method: Sympatec (laser, dry process)

Purpose of the test: Determination of particle size distribution

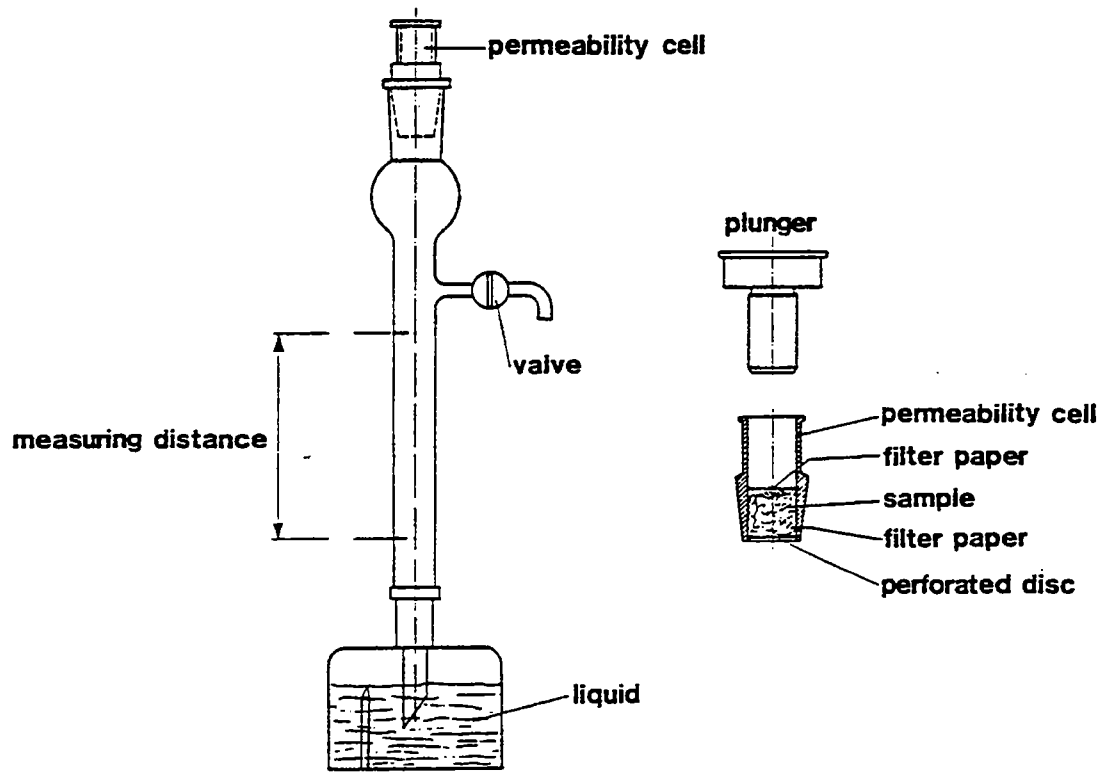
Test equipment:



- Test procedure:
- Zero calibration
 - Sample preparation: 20 - 50 g (< 875 μm)
 - Test run
 - Automatic display of particle size distribution
- Total testing time (31 particle fractions): 5 min.
 Sieve range:
 1 - 175 μm
 1 - 350 μm
 1 - 875 μm

SPECIFIC SURFACE TEST	
Test method:	BLAINE
Purpose of the test:	Determination of specific surface of cement

Test equipment:



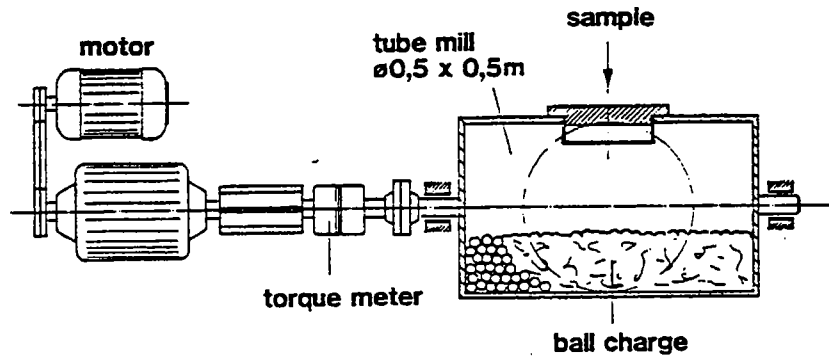
TEST PROCEDURE :	→ Sample preparation	: 2,7 g
	→ Three test runs	
	→ Time measurement	t
	→ Determination of bulk weight	ε } cm ² /g
	Total testing time	: 5 - 10 min
	Measuring range	: 1000 - 8000 cm ² /g

GRINDABILITY TEST

Test method: **HOLDERBANK**

Purpose of the test: Determination of energy input for grinding of raw material and clinker

Test equipment:



-
- TESTING PROCEDURE** :
- Sample preparation : 10 kg (< 12mm)
 - Test run : stepwise (100-200 revolutions)
 - Sieve test : % Residue (90 μ m)
 - Torque measurement } → kWh/t
 - Number of revolutions }
-

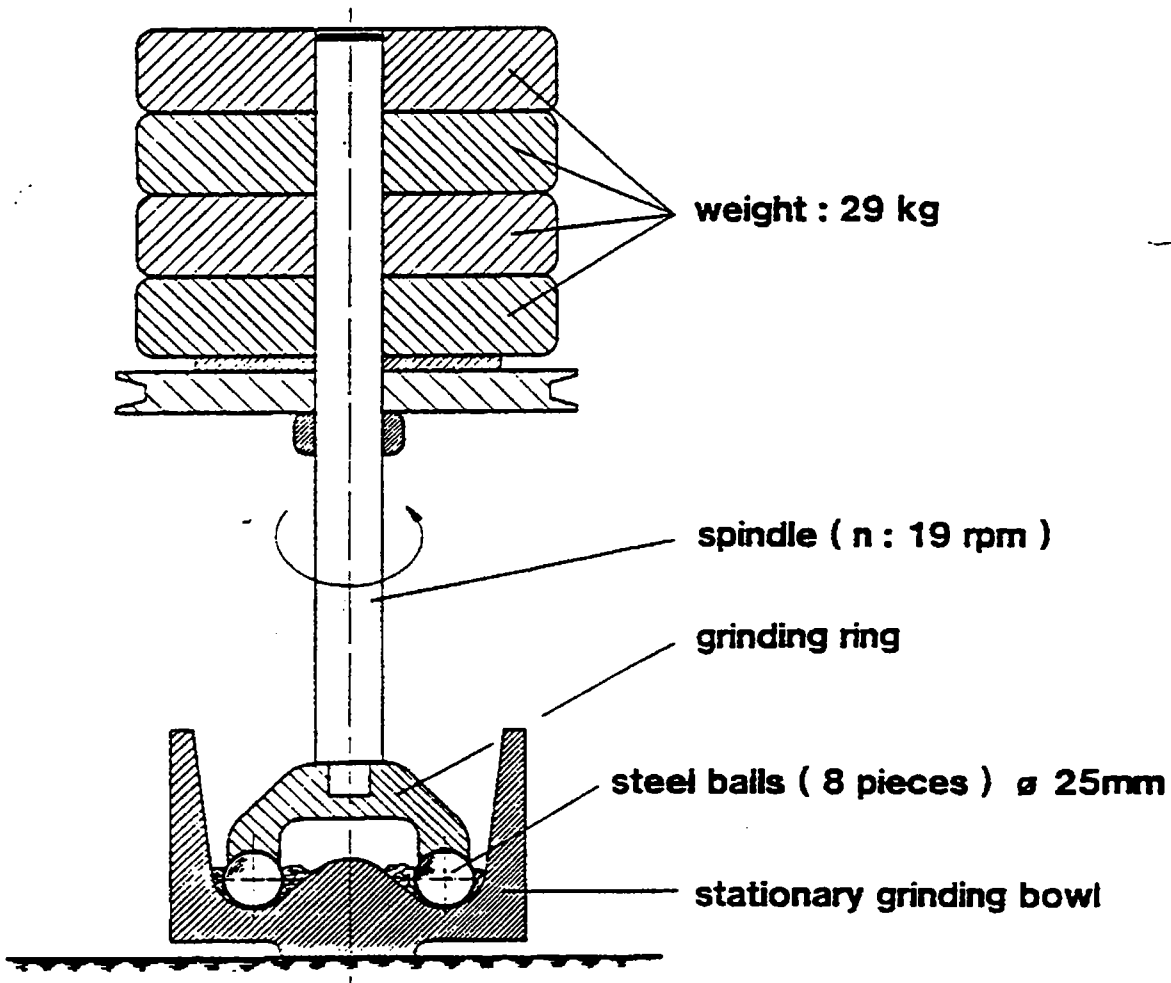
- TEST EVALUATION** :
- Plotting of grindability curve
 - kWh/t in function of product fineness
 - Converting of test results (scale-up) to industrial mill
 - mill motor size of tube mill

GRINDABILITY TEST

Test method: **HARDGROVE**

Purpose of the test: Determination of energy input for grinding of coal

Test equipment:



Test procedure:	→ Sample preparation:	50 g (590 - 1190 μ m)
	→ Test run:	60 revolutions
	→ Sieve test:	D = weight of particles < 90 μ m

Test evaluation:	→ Calculation of Hardgrove Index H
	→ Comparison with standard material
	→ Conversion to energy input (kWh/t)
	→ mill motor size of coal mill

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